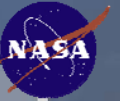


Energy Goals & Safety Challenges for Future Space Exploration

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NASA Johnson Space Center, Houston, TX
September 2014



PROPULSION & POWER DIVISION



Outline

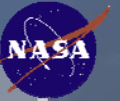
- Power Needs for Exploration
- Technology Programs to Achieve Safe & High-Energy Power Goals
- Work carried out by Battery Group at NASA-JSC
- Summary & Conclusions



Power Goals & Challenges

- Future exploration needs include very high-energy density (~ 500 Wh/kg) batteries
- Batteries need to be safe under credible off-nominal conditions (no venting, fire, thermal runaway)
- Batteries need to perform under extreme thermal environments (200 to 400 °C for Venus; -60 °C for Lunar and Mars Rovers)
- Modular power systems must go across different applications:
 - Space vehicles
 - Astronaut Suit
 - Surface mobility systems
 - Habitats





Surface Systems (Mobility) Pressurized Rover



Preliminary Power Requirements:

Safe, reliable operation

>150 Wh/kg at battery level

~ 500 cycles

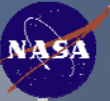
270 V

Operation Temp: 0 to 30 °C

Maintenance-free operation



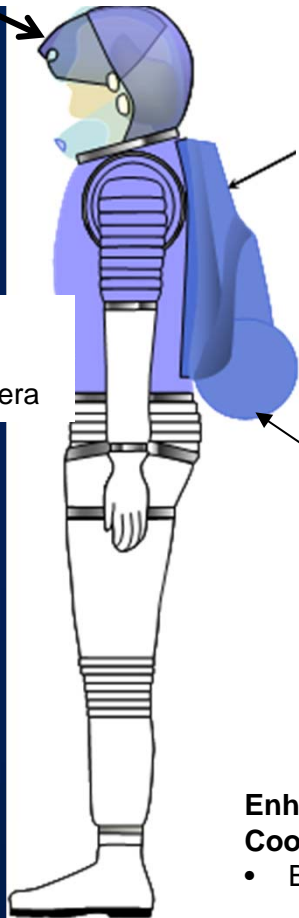
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Advanced Extravehicular Activity (AEVA) Suit

Enhanced Helmet Hardware:

- Lighting
- Heads-Up-Display
- SUT Integrated Audio



Power/CAI:

- C3I processing
- Expanded set of suit sensors
- Advanced caution & warning
- Displays & productivity enhancements

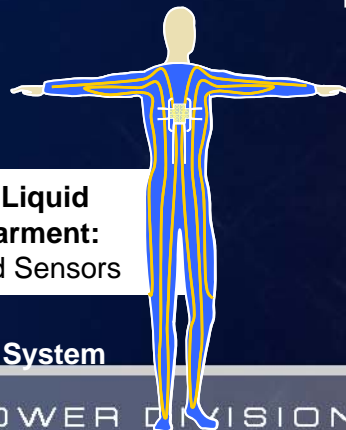
PLSS:

- Fan, pump, ventilation subsystem processor; heater, controllers, & valves

Enhanced Liquid Cooling Garment:

- Bio-Med Sensors

PLSS: Primary Life Support System



- Power to support 8-hour EVA provided by battery in Portable Life Support System

- Preliminary battery design goals:

- Human-safe operation
- 144 W (average) and 233 W (peak) power

Assumes 1% connector loss and 30% margin for growth in power requirements

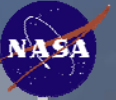
- No more than 5 kg mass and 3 liter volume
- 100 cycles (use every other day for 6 months)
- 8-hour discharge to at most 85% depth-of-discharge
- Temperature controlled to 0 to +30 °C

- Secondary batteries are considered critical for EVA Suit 2.

Current Suit Batteries:

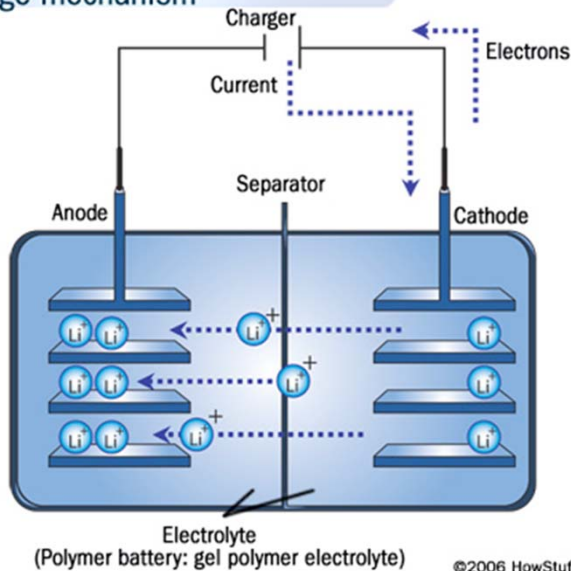
- EMU: 20.5 V; min 26.6 Ah (7 hr EVA), 9A peak, 5 yr, <15.5 lbs (7 kg), 30 cycles
- SAFER: 42 V; 4.2 Ah (in emergency only)
- REBA: 12.5 V, 15 Ah, (7 hr EVA); 5 yr, ~6 lbs (2.7 kg)
- EHIP: 6 V, 10.8 Ah; (7 hr EVA); 5 yr, ~1.8 lbs (0.8 kg)



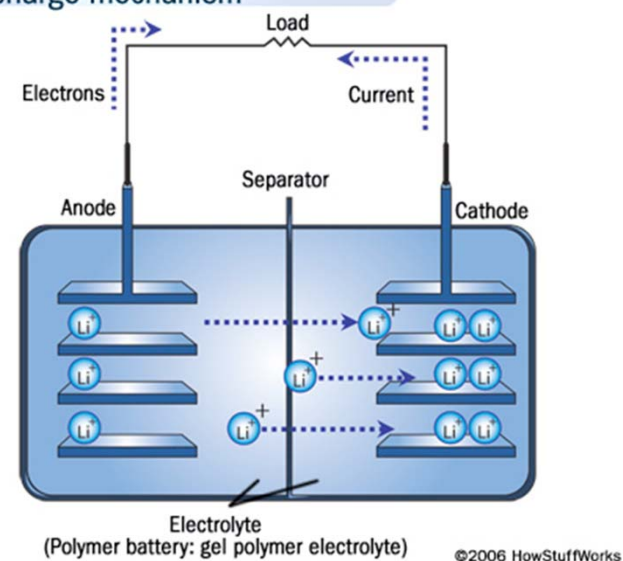


Lithium-ion Chemistry

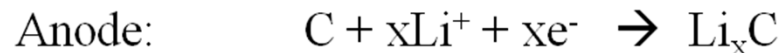
Lithium-ion rechargeable battery
Charge mechanism



Lithium-ion rechargeable battery
Discharge mechanism



The half reactions are:



The overall reaction is: $\text{LiMO}_2 + \text{C} \rightleftharpoons \text{Li}_x\text{C} + \text{Li}_{1-x}\text{MO}_2$

Cathode: Lithium metal oxide
(LiCoO_2 , $\text{LiNi}_{0.3}\text{Co}_{0.7}\text{O}_2$, LiNiO_2 ,
 LiV_2O_5 , LiMn_2O_4 , $\text{LiNiO}_{0.2}\text{Co}_{0.8}\text{O}_2$)

Anode: Carbon compound (graphite, hard
carbon, etc. or Li titanate or Sn alloy, Si alloy or
Si/C)

Electrolyte: LiPF_6 & a combination of carbonates

Separator: PE or PP/PE/PP



Key Performance Parameters for Battery Technology Development

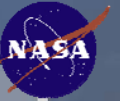
Customer Need	Performance Parameter	State-of-the-Art	Current Value	Threshold Value	Goal
Safe, reliable operation	No fire or flame	Instrumentation/controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA	Preliminary results indicate a moderate reduction in the performance with flame retardants & non-flammable electrolytes	Benign cell venting without fire or flame & reduce the likelihood & severity of a fire if a thermal runaway occurs	Tolerant to electrical & thermal abuse such as over-temperature, over-charge, reversal, & external short circuit with no fire or flame
Specific energy <u>Lander:</u> 150 – 210 Wh/kg 10 cycles <u>Rover:</u> 150 – 200 Wh/kg <u>EVA:</u> 200 – 300 Wh/kg 100 cycles	Battery-level specific energy*	90 Wh/kg at C/10 & 30°C 83 Wh/kg at C/10 & 0°C (MER rovers)	130 Wh/kg at C/10 & 30°C 120 Wh/kg at C/10 & 0°C	135 Wh/kg at C/10 & 0°C “High-Energy”** 150 Wh/kg at C/10 & 0°C “Ultra-High Energy”**	150 Wh/kg at C/10 & 0°C “High-Energy” 220 Wh/kg at C/10 & 0°C “Ultra-High Energy”
	Cell-level specific energy	130 Wh/kg at C/10 & 30°C 118 Wh/kg at C/10 & 0°C	150 Wh/kg at C/10 & 0°C	165 Wh/kg at C/10 & 0°C “High-Energy” 180 Wh/kg at C/10 & 0°C “Ultra-High Energy”	180 Wh/kg at C/10 & 0°C “High-Energy” 260 Wh/kg at C/10 & 0°C “Ultra-High Energy”
	Cathode-level specific capacity Li(Li,NiMn)O ₂	140 – 150 mAh/g typical	Li(Li _{0.17} Ni _{0.25} Mn _{0.58})O ₂ : 240 mAh/g at C/10 & 25°C Li(Li _{0.2} Ni _{0.13} Mn _{0.54} Co _{0.13})O ₂ : 250 mAh/g at C/10 & 25°C 200 mAh/g at C/10 & 0°C	260 mAh/g at C/10 & 0°C	280 mAh/g at C/10 & 0°C
	Anode-level specific capacity	320 mAh/g (MCMB)	320 mAh/g MCMB 450 mAh/g Si composite	600 mAh/g at C/10 & 0°C with Si composite	1000 mAh/g at C/10 0°C with Si composite
Energy density Lander: 311 Wh/l Rover: TBD EVA: 240 – 400 Wh/l	Battery-level energy density	250 Wh/l	n/a	270 Wh/l “High-Energy” 360 Wh/l “Ultra-High”	320 Wh/l “High-Energy” 420 Wh/l “Ultra-High”
	Cell-level energy density	320 Wh/l	n/a	385 Wh/l “High-Energy” 460 Wh/l “Ultra-High”	390 Wh/l “High-Energy” 530 Wh/l “Ultra-High”
Operating environment 0°C to 30°C, Vacuum	Operating temperature	-20°C to +40°C	-50°C to +40°C	0°C to 30°C	0°C to 30°C

Assumes prismatic cell packaging for threshold values. Goal values include lightweight battery packaging.

* Battery values are assumed at 100% DOD, discharged at C/10 to 3.0 volts/cell, & at 0°C operating conditions

** “High-Energy” = Exploration Technology Development Program cathode with MCMB graphite anode

“Ultra-High Energy” = Exploration Technology Development Program cathode with Silicon composite anode



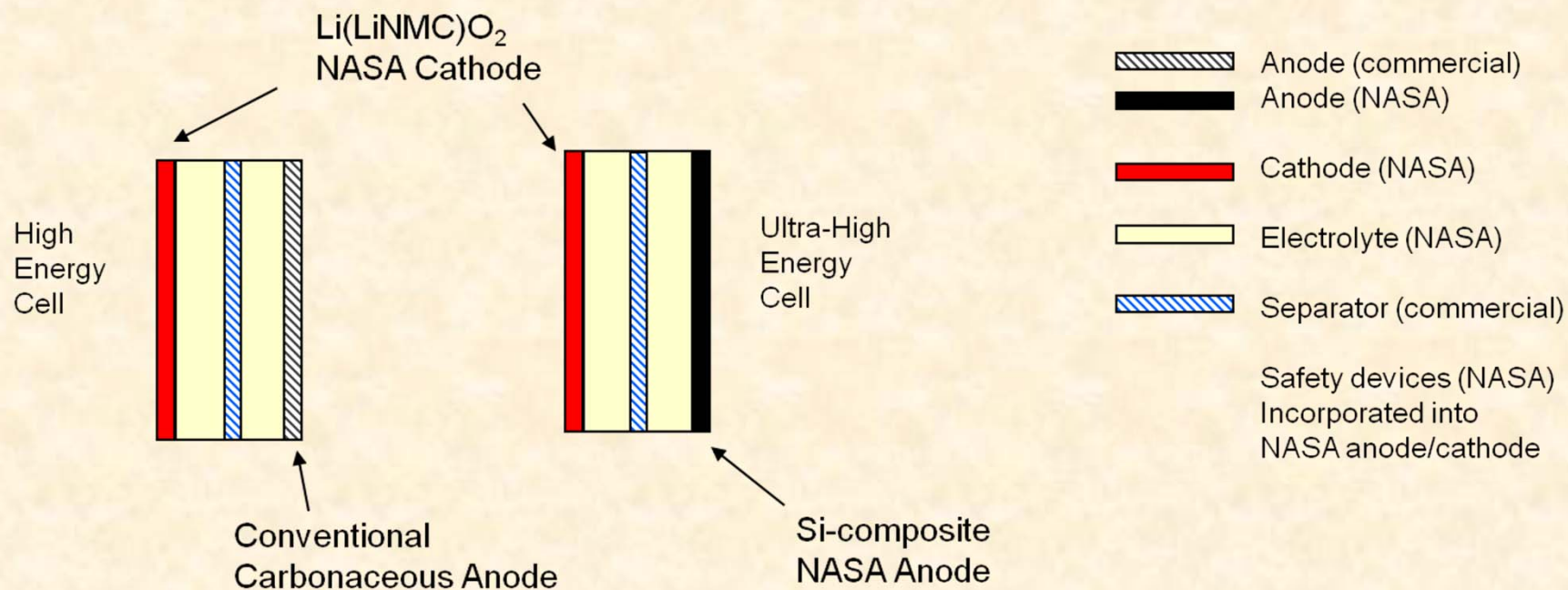
Space Power Systems Li-ion Cell Development

- **Component-level goals** are being addressed through a combination of NASA in-house materials development efforts, NRA contracts, & grants
- Materials developed will be delivered to NASA & screened for their electrochemical & thermal performance, & compatibility with other candidate cell components
- Other activities funded through NASA can be leveraged – NASA SBIR Program & IPP
- Leveraging other government programs (Department of Defense - DoD, Department of Energy - DOE) for component-level technology
- Leveraging other venues through SAAs that involve industry partners such as Exxon; non-profit organizations such as UL, etc.





Energy Storage Project Cell Development for Batteries



"High-Energy" Cell

Baseline for EVA & Rover

Lithiated-mixed-metal-oxide cathode/Graphite anode

Li(LiNMC)O₂ / conventional carbonaceous anode

150 Wh/kg (100% DOD) at battery-level 0°C C/10

80% capacity retention at ~**2000** cycles

"Ultra-High Energy" Cell

Upgrade for EVA & Altair, possibly Rover

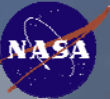
Lithiated-mixed-metal-oxide cathode/Silicon composite anode

Li(LiNMC)O₂ / silicon composite

220 Wh/kg (100% DOD) at battery-level 0°C C/10

80% capacity retention at ~**200** cycles





Cell Development

- **Assess components**
 - Build & test electrodes & screening cells (Coin & Pouch)
 - Provide manufacturing perspective from inception
- **Scale-up components**
 - Transition components from the lab to the manufacturing floor
- **Build baseline cells (10 Ah):**
 - Graphite anode (MPG-111) with NCA
 - Determine baseline performance
- **Build & test evaluation cells (10 Ah):**
 - Determine component interactions
 - Determine cell-level performance

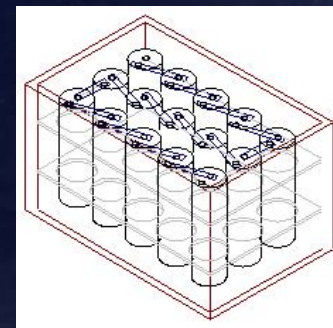


Coin Cell

Pouch Cell

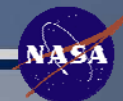


DD Cells



Cathode Development

Led by JPL



- **Goals:**
 - Specific capacity of 280 mAh/g at C/10 & 0°C to 3.0 V
 - High-voltage operation to 4.8 V
 - Improved thermal stability over conventional Li-ion cathodes

System	Sp. Capacity, mAh/g		Voltage vs Li	Sp. Energy, Wh/kg (Cathode Alone) vs Li	TRL	Manufacturer (and Heritage)
	Theoretical	Experimental				
LiCoO ₂ (Lithiated Cobalt Oxide)	274	137	4.15	569	7-9	ABSL (Kepler, Aquarius, SMAP, EVA)
Li(NCO) (LiNi _{0.8} Co _{0.2} O ₂)	274	165	4.05	668	7-9	Yardney (Mars Missions, MER, MSL, GRAIL, Juno)
Li(NCA) (LiNi _{0.8} Co _{0.15} Al _{0.05} O ₂)	279	165	4.05	668	7-9	SAFT, Quallion, Yardney (Space Station, PGT)
Li (NMC) (0.33:0.33:0.33)	278	180	4.3	774	4	No
Li (Li,NMC)O ₂ Layered-layered Composites of LiMn ₂ O ₃ :LiMO ₂	330	275	4.5	1238	2-3	No
LiFePO ₄ (Olivine)	170	160	3.6	576	5	A123 (None)
LiCoPO ₄ (Olivine)	166	155	4.8	744	1-2	No
LiMnPO ₄ (Olivine)	171	160	4.3	688	1-2	No
LiMn ₂ O ₄ (Cubic Spinel)	148	120	4	480	4	No
LiMn _{1.5} Ni _{0.5} O ₄ (5 V Spinel)	148	130	4.8	624	4	No

Courtesy: Kumar Bugga, JPL

Cathode Efforts

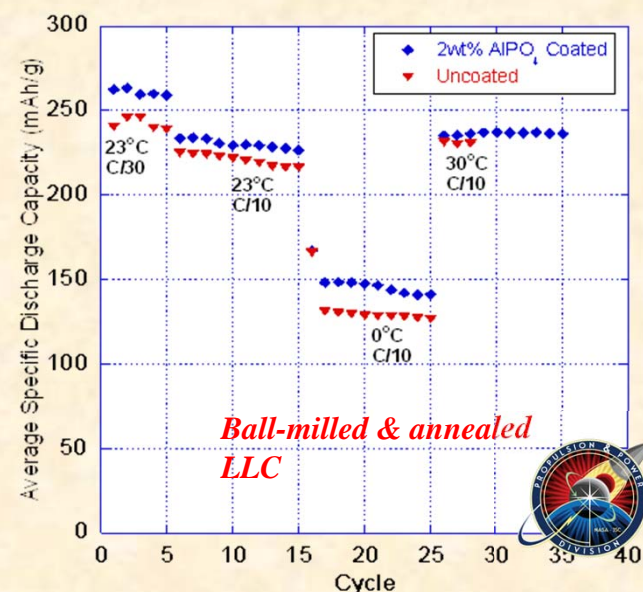
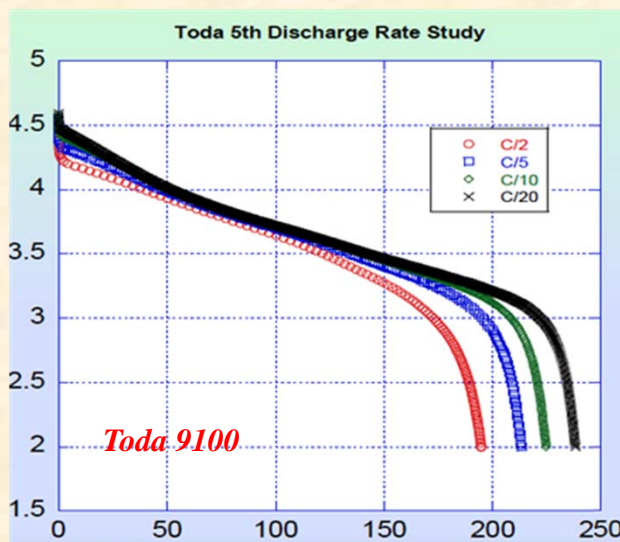
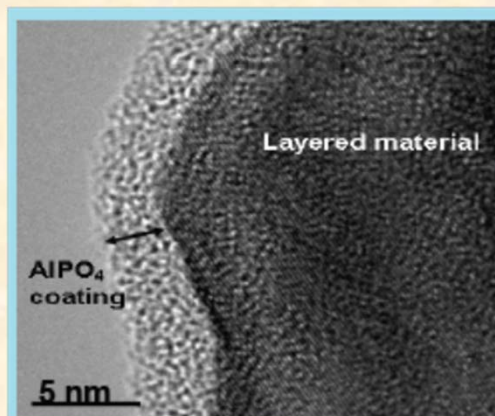


Lithium Manganese Rich Layered-Layered Composites

Strategies:

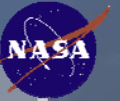
- Determine best ratio of Li, Ni, Mn & Co to maximize the capacity
- Add surface coating on cathode particles to improve the interfacial properties (reduces electrolyte reactivity & facilitates charge transfer)
- Improve morphology to create ultrafine spherical particles (vary synthesis method)

- High capacity > 250 mAh/g achieved from optimized composition of transition metal ratio & Li content
- High tap densities (1.5-2.0 g/cc) & spherical morphology realized from hydroxide precursor synthesis
- Demonstrated improved performance (high-reversible & low-irreversible capacity, & cyclic & thermal stability with surface coatings, (AlPO_4 & LiCoPO_4)
- Developed new efficient coatings amenable for scale-up
- Evaluated cathode material of similar composition from several commercial sources



Courtesy: Kumar Bugga, JPL

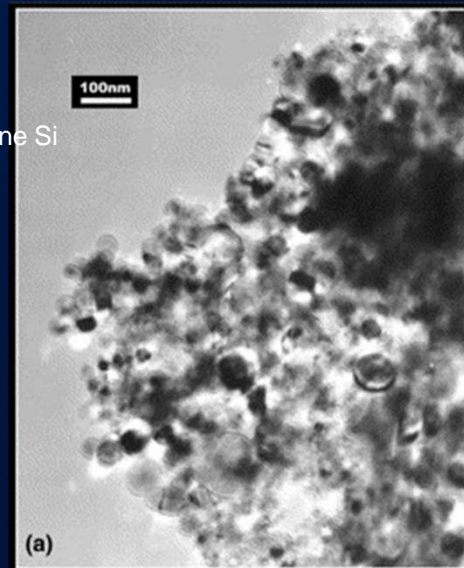




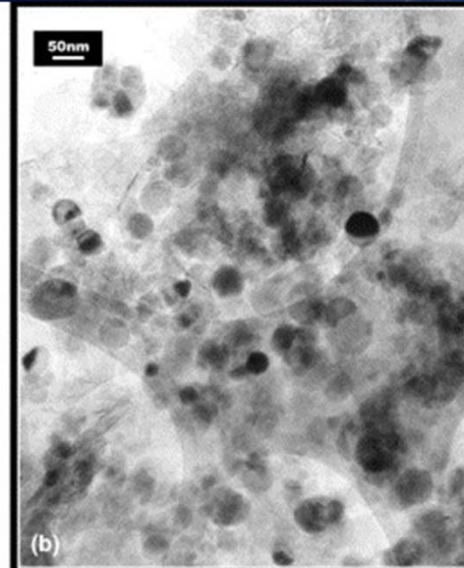
Anode Development Led by NASA GRC

- **Goal:**
 - 1000 mAh/g at C/10 (10-hr discharge rate) & 0°C
 - Over 3 times the capacity of SOTA Li-ion anodes
 - Threshold value = 600 mAh/g at C/10 & 0°C

TEM of nanocrystalline Si



TEM of nanocrystalline Si-C composites



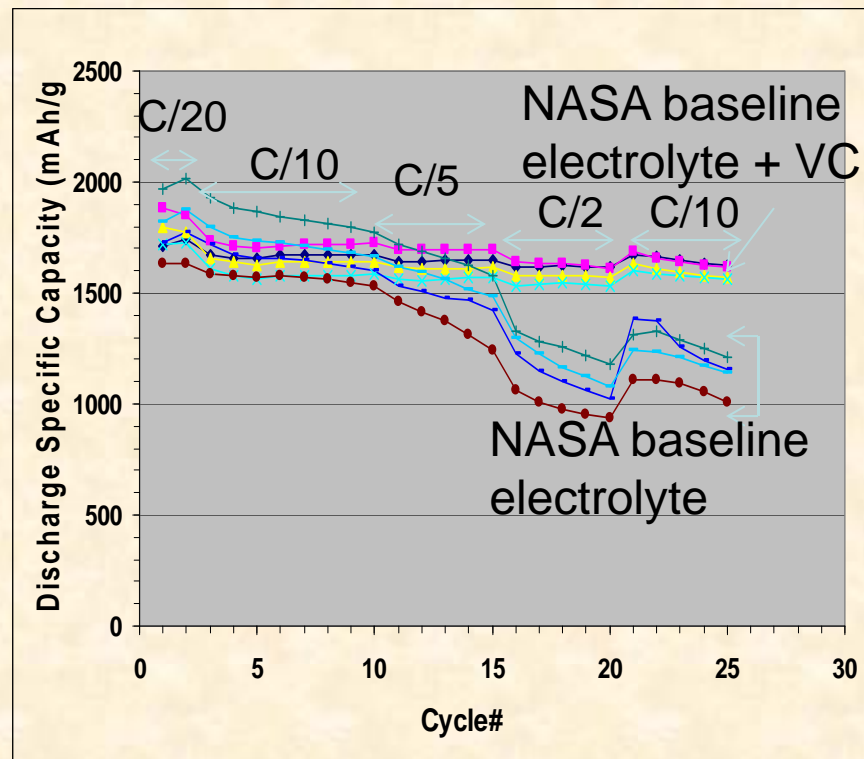
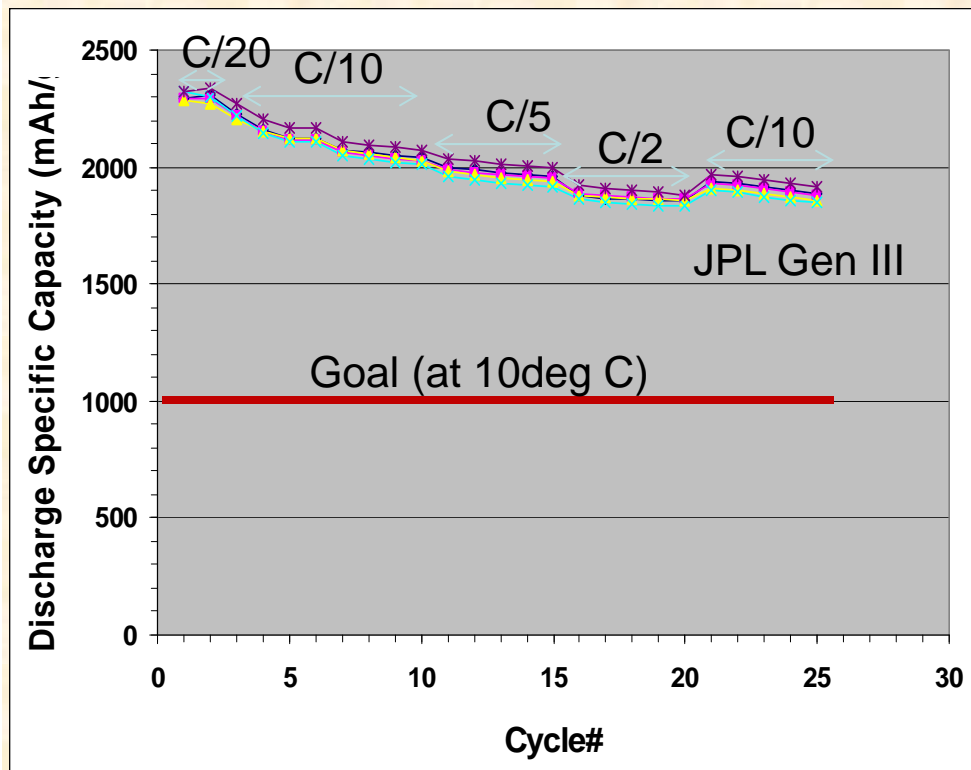


Si Anode Material Scale-up & Test



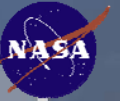
Si Anode made by Saft (2nd, calendared)

Si Anode (GT-4B)



- Saft successfully scaled up Si anode:
 - Si anode made by Saft shows the highest capacity & excellent rate capability
 - Cycling that is much higher than 1000 mAh/g (the goal)
- VC in baseline electrolyte improves rate capability cycling





Current State for Safety of Li-ion Batteries

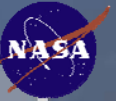
Although the chemistry is one that can provide very high-energy density currently, it is not the safest

- NASA human-rated safety requirement is two-fault tolerance to catastrophic failures – leakage of electrolyte (toxicity hazard), fire, thermal runaway

Hazards are encountered in Li-ion cells/ batteries typically during the following events:

- Overcharge/overvoltage
- External shorts
- Repeated overdischarge with subsequent charge
- High thermal environments
- Internal shorts





Background

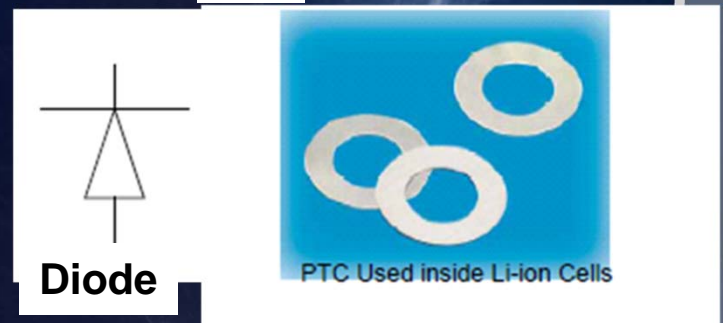
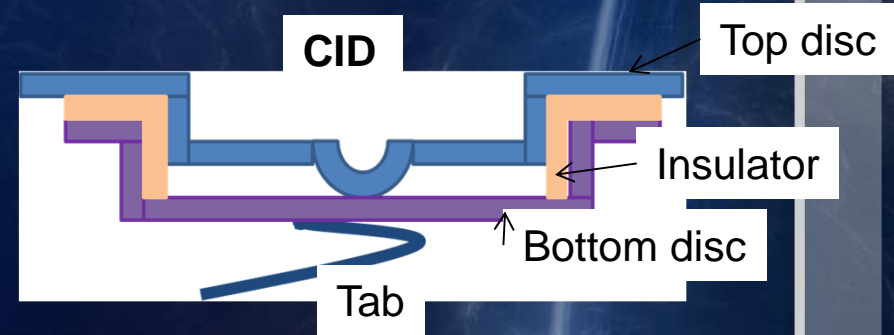
- Lithium-ion cells, whether cylindrical, prismatic, etc., have different forms of internal protective devices:

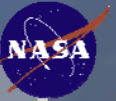
- PTC
- CID
- Tab/lead meltdown (fusible link type)
- Bimetallic disconnects

Lithium-ion battery designs have several external protective devices:

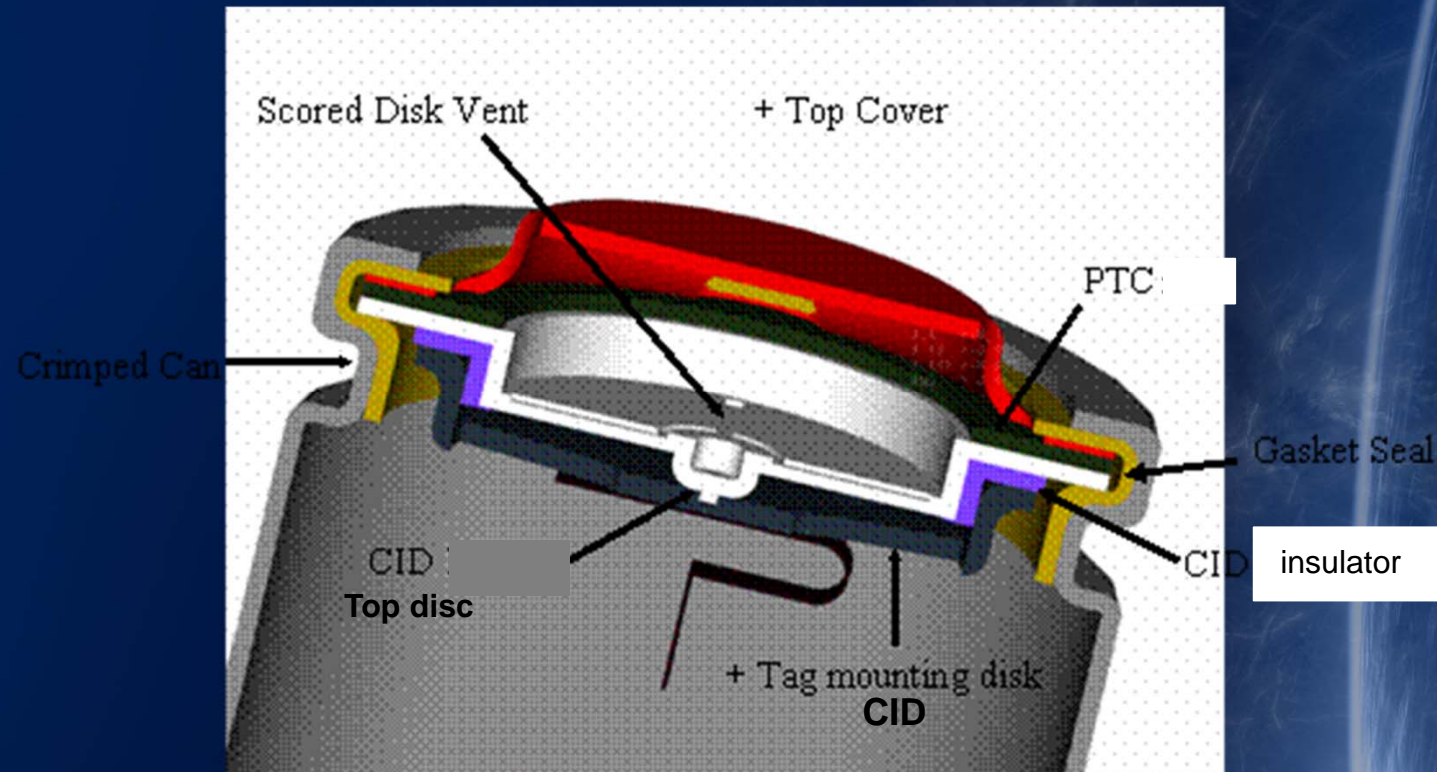
- Diodes
- PTC/polyswitch
- Thermal fuses (hard blow or resettable)
- Circuit boards with specialized wire traces

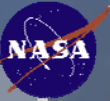
- Manufacturing quality is critical to prevent internal short hazards – cell quality as well as uniformity of cell performance is important



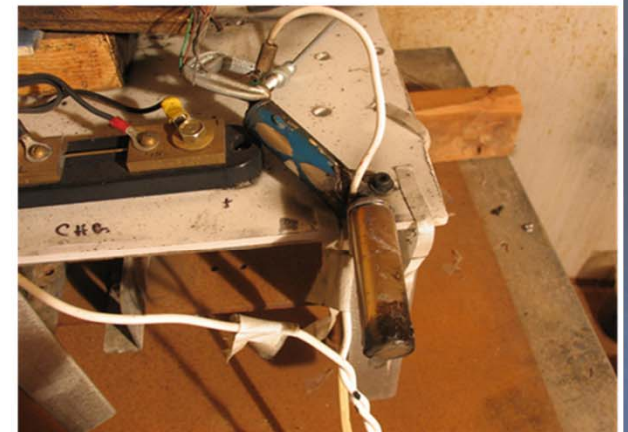
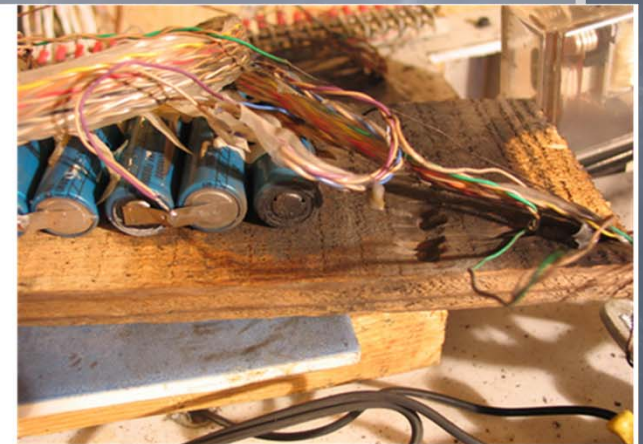
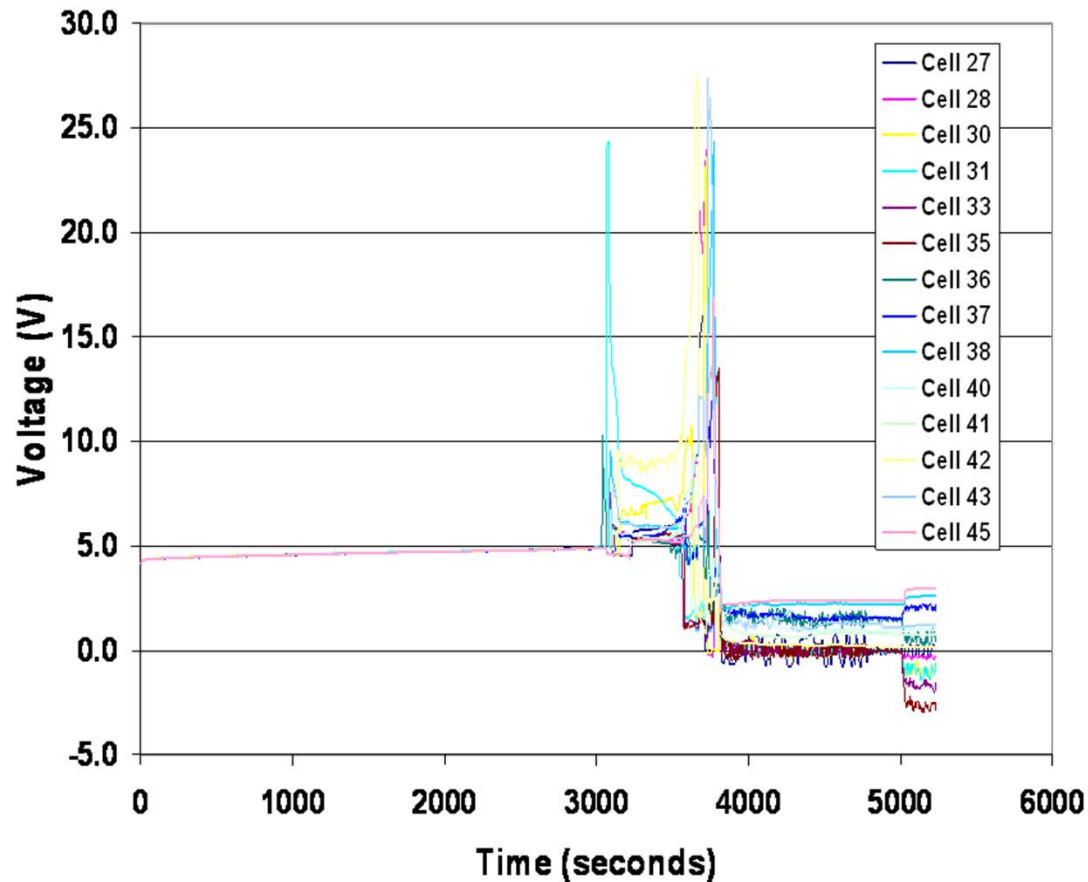


Schematic of Cell Header Portion



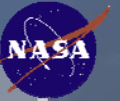


Overcharge Test on a 14-Cell String Showing Cell Voltages for the Sony Li-ion Cells

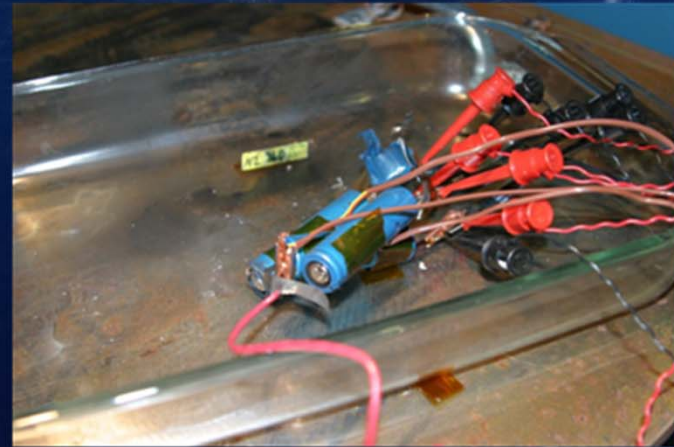
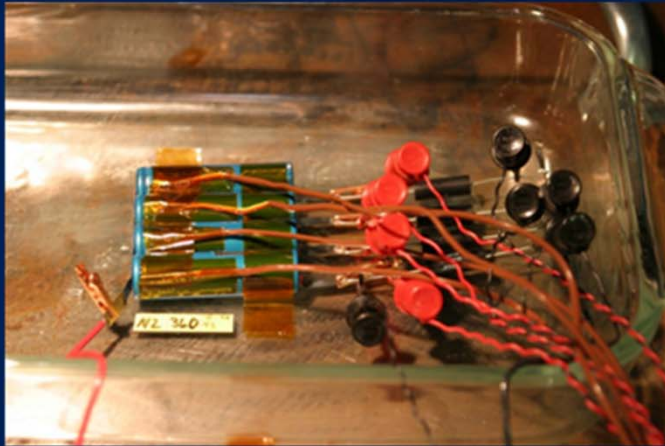


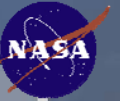
Missing : 27, 28, 30 and 31

**Cells 37, 38 and 45 showed no visible
Signs of venting**

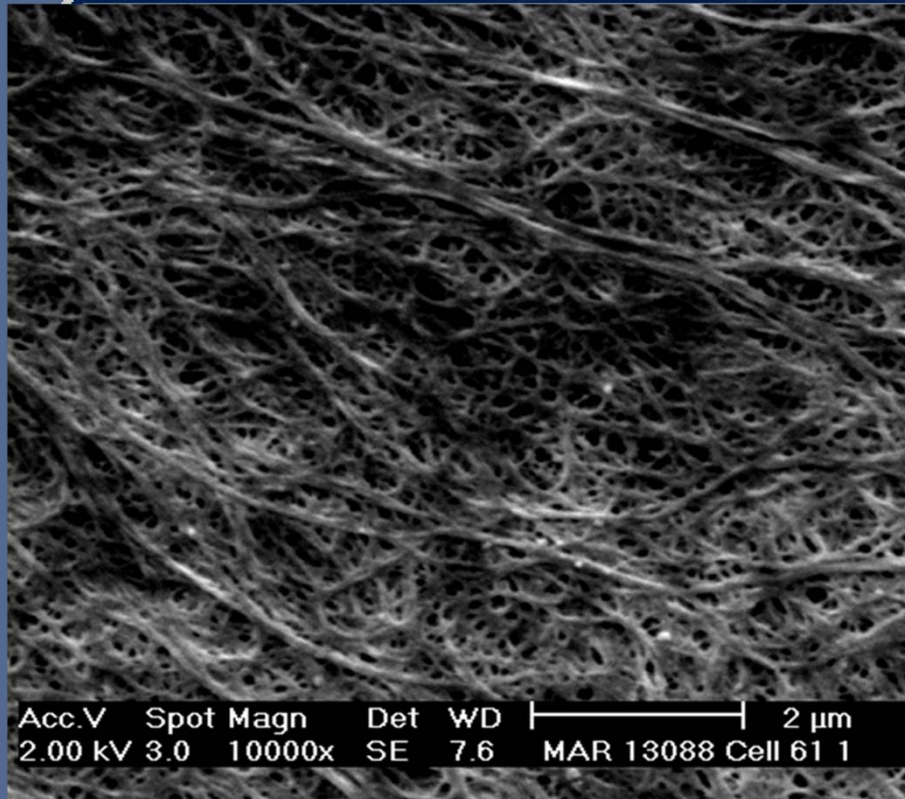


48V 6A Overcharge on 4P Battery

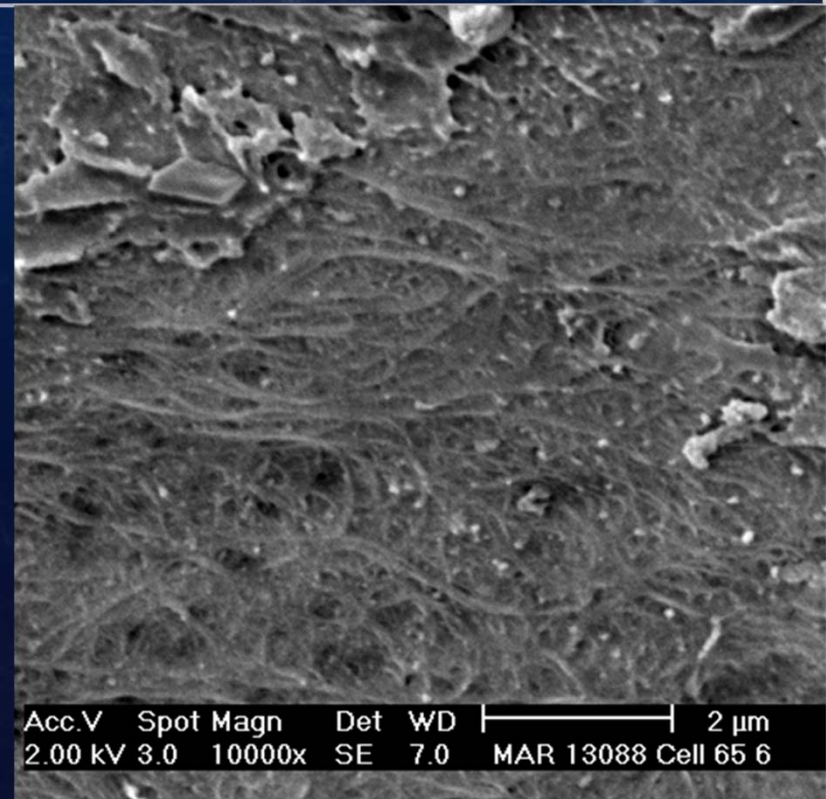




Current Separators in Commercial-off-the-Shelf Li-ion Cells



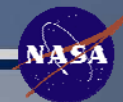
Unactivated Separator



Activated Separator

Shut-down temperature is very close to the temperature at which initiation of thermal runaway occurs.





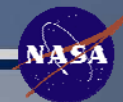
Electrolytes

Electrolyte Selection Criteria

- High conductivity over a wide range of temperatures
 - 1 mS cm⁻¹ from -60 to 40°C
- Wide liquid range (low melting point)
 - -60 to 75°C
- Good electrochemical stability
 - Stability over wide voltage window (0 to 4.5V)
 - Minimal oxidative degradation of solvents/salts
- Good chemical stability
- Good compatibility with chosen electrode couple
 - Good SEI characteristics on electrode
 - Facile lithium intercalation/de-intercalation kinetics
- Good thermal stability
- Good low temperature performance throughout life of cell
 - Good resilience to high temperature exposure
 - Minimal impedance build-up with cycling or storage or both

Additionally, the electrolyte solutions should ideally have low flammability & be non-toxic !!



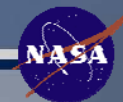


Flame Retardant Additives in Li-ion Cells for Improved Safety Characteristics

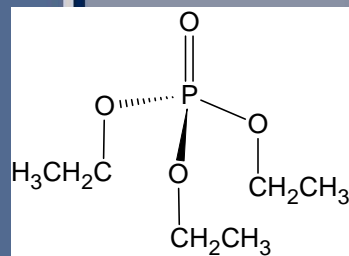
- Modification of electrolyte is one of the least invasive & cost effective ways to improve the safety characteristics of Li-ion cells. Common approaches include using the following ingredients:
 - ◊ Use of Redox shuttles (to improve safety on overcharge)
 - Ionic liquids (have inherently low flammability, because of low vapor pressure)
 - Lithium salt modification
 - Flame retardant additives
 - ◊ Use of non-flammable solvents (i.e., halogenated solvents)

Of these approaches, using flame retardant additives has been observed to possess the least impact upon cell performance.

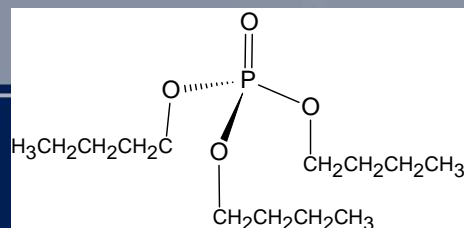




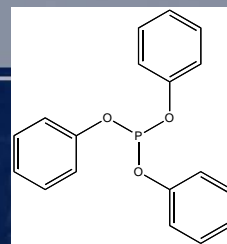
Development of Electrolytes Containing Flame Retardant Additives



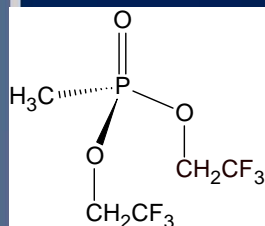
Triethyl phosphate (TEP)



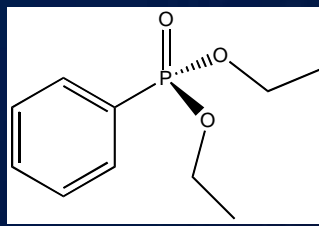
Tributyl phosphate (TBP)



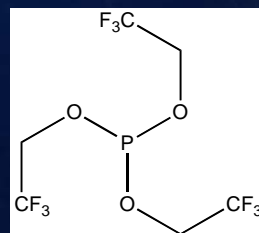
Triphenyl phosphite (TPPi)



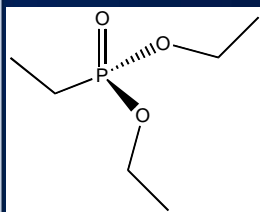
Bis-(2,2,2-trifluoroethyl)methyl phosphonate (BTFEMP)



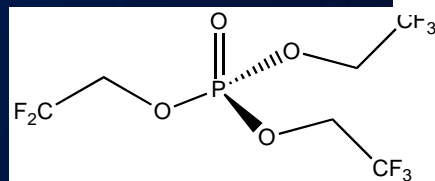
Diethyl phenylphosphonate (DPP)



Tris(2,2,2-trifluoroethyl) phosphite (TFPi)

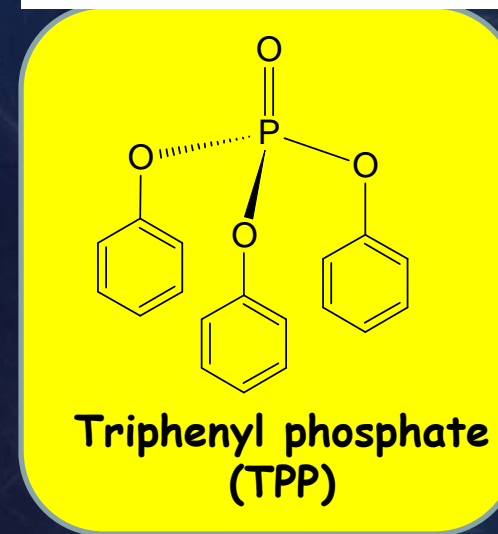


Diethyl ethylphosphonate (DEP)



Tris(2,2,2-trifluoroethyl) phosphate (TFPa)

TPP identified as being the most robust flame retardant additive

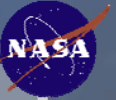


Electrolytes with the various additives were incorporated into three electrode cells with various cathodes and anodes, and Li metal reference electrodes

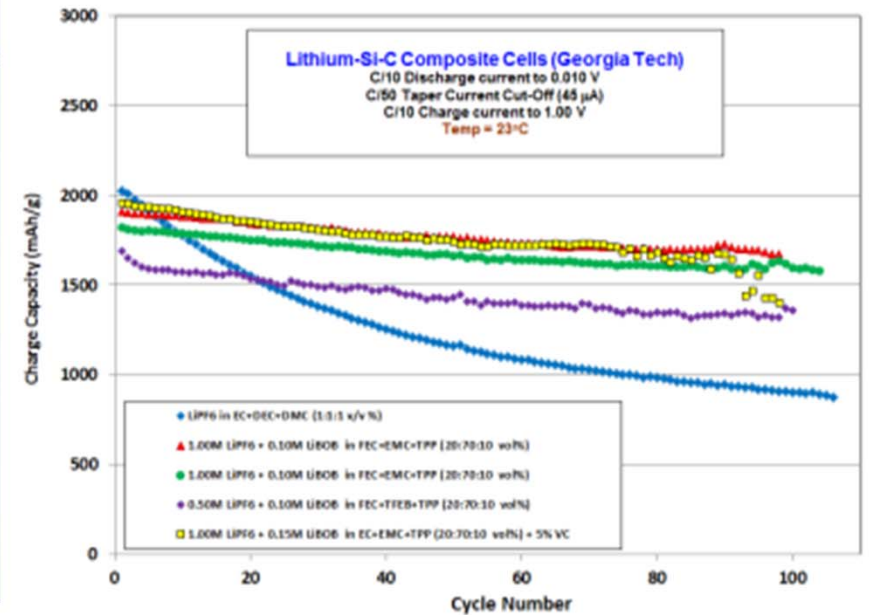
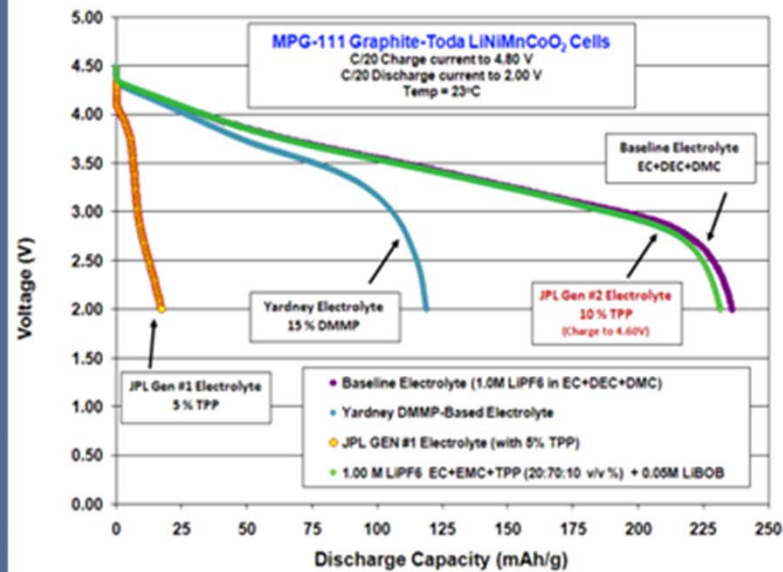
- 1) Y. E. Hyung, D. R. Vissers, K. Amine
J. Power Sources, **2003**, 119-121, 383
- 2) K. Xu, M. S. Ding, S. Zhang, J. L. Allen, T. R. Jow
J. Electrochem. Soc. **2002**, 149, A622

J. Electrochem. Soc. **2002**, 149, A622

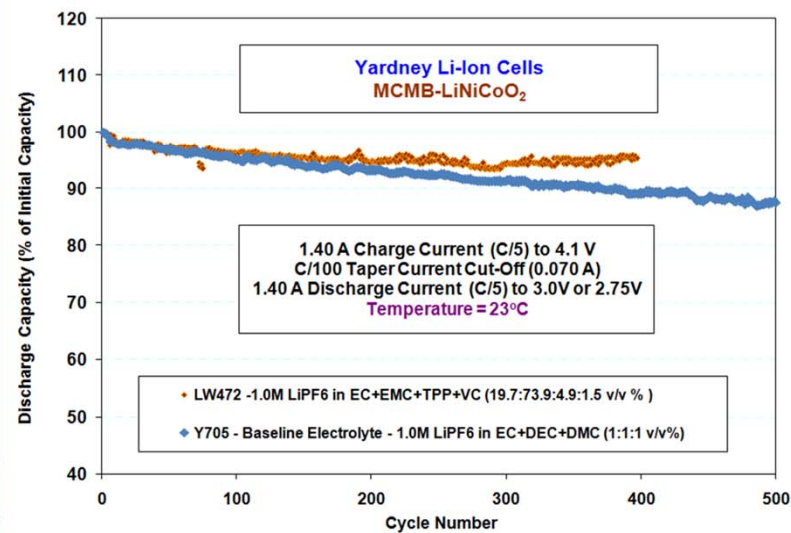


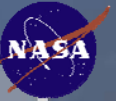


Electrolytes



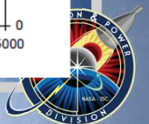
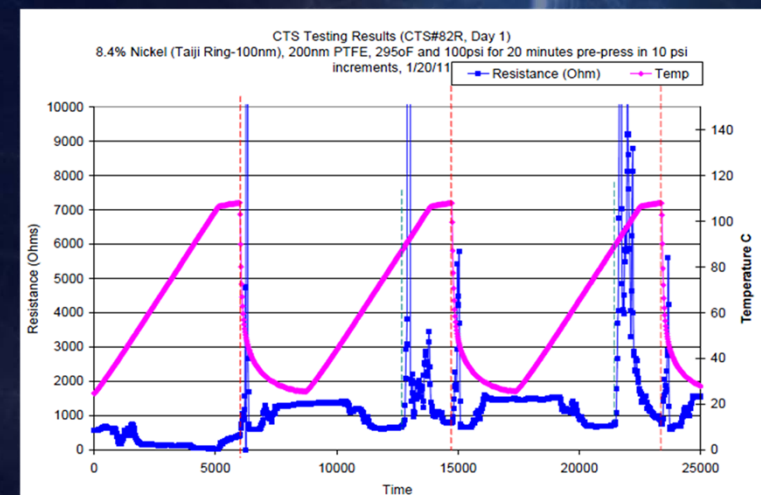
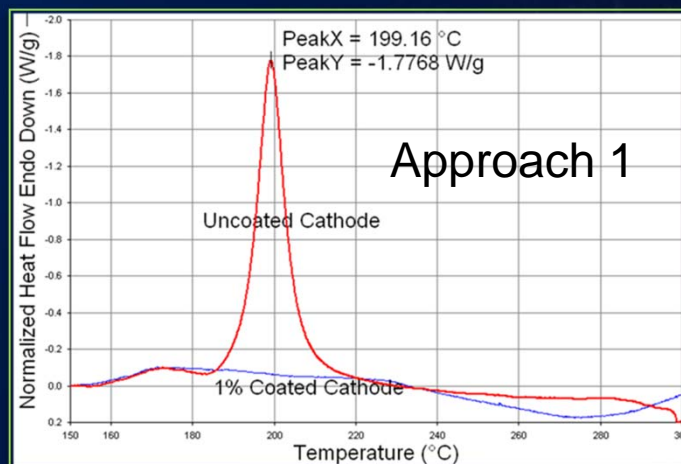
DMMP: Dimethyl Methyl phosphanate
VC: Vinylene carbonate
LiBOB: Lithium bisoxalatoborate

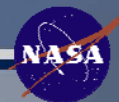




Safety Component Development Led by NASA JSC

- Development of internal cell materials (active or inactive) designed to improve the inherent safety of the cell
 - Approach 1: Develop a high-voltage stable (phosphate type) coating on cathode particles to increase the safe operating voltage of the cell & reduce the thermal dissipation by the use of a high-voltage stable coating material (Nano-sized material)- Physical Sciences Inc (PSI)
 - Approach 2: Develop a composite thermal switch to shutdown cell reactions safely using coatings on the current collector substrates (nano-particle metals).

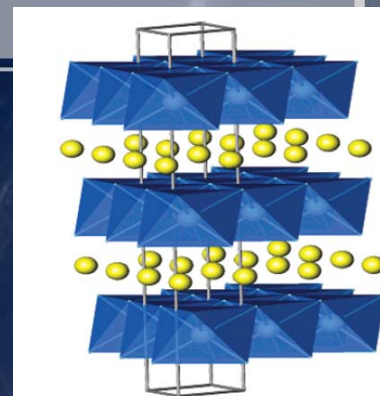




Summary of Current Technology Work

- **High-Energy NMC Cathodes**

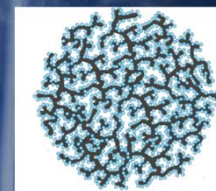
- Scale-up of the NASA-process
- High Irreversible capacity loss, especially with uncoated cathode
 - Non-availability of lithium at the anode for the irreversible capacity
- Electrolyte consumption (& anode dry-out) as a result of O_2 evolved in formation
- Transition metal dissolution in electrolytes (Mn, Ni, & Co)
- Low power densities, more noticeable with high electrode loadings
- Voltage slump during cycling because of “spinel formation”



HE-NMC Cathode

- **Si Composite Anodes**

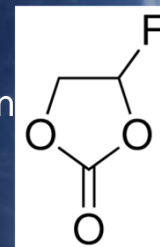
- Limited cycle life (< 500)
- High irreversible capacity (10-20%) & poor coulombic efficiency
- Unknown compatibility with the high-energy cathode (dissolved metal?)



Nano-Si anode

- **Electrolytes**

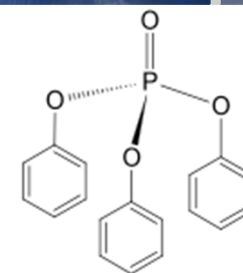
- Changes to the cathode or anode may require electrolyte modification



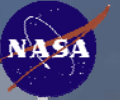
FEC

- **Cell Design**

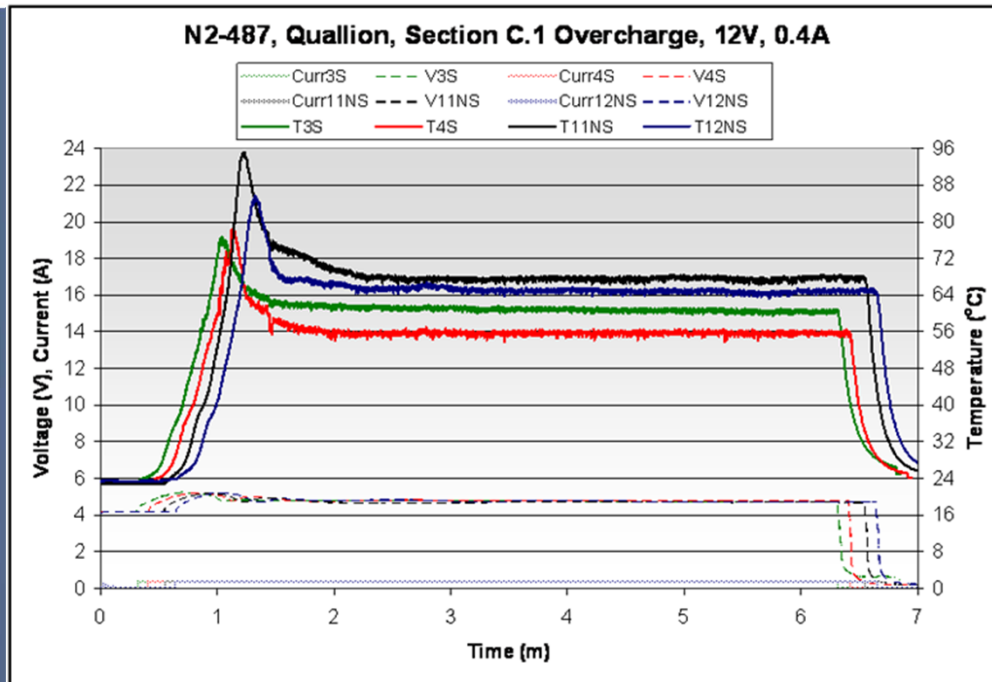
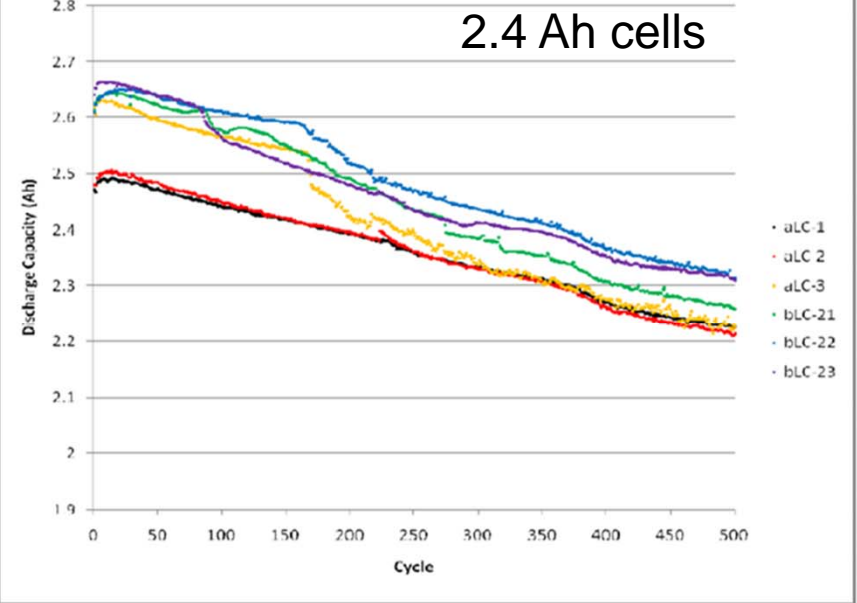
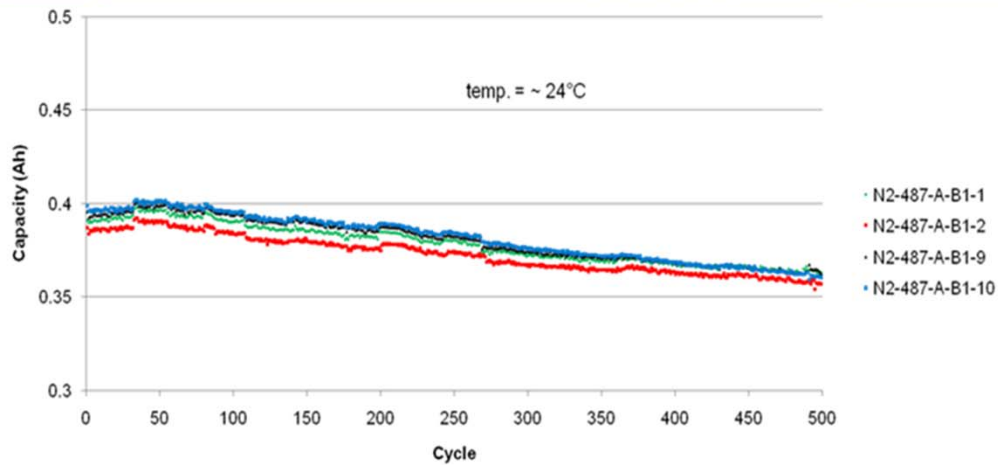
- Test for performance & safety

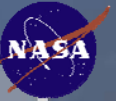


Triphenyl phosphate (TPP)



SafeLyte[®] Additive (IPP)





Li-O₂ & Li-air: ~TRL 2

Characteristics:

- Ultra-low mass
- 600 to 2200 mAh/g of cathode depending upon current density (rate)

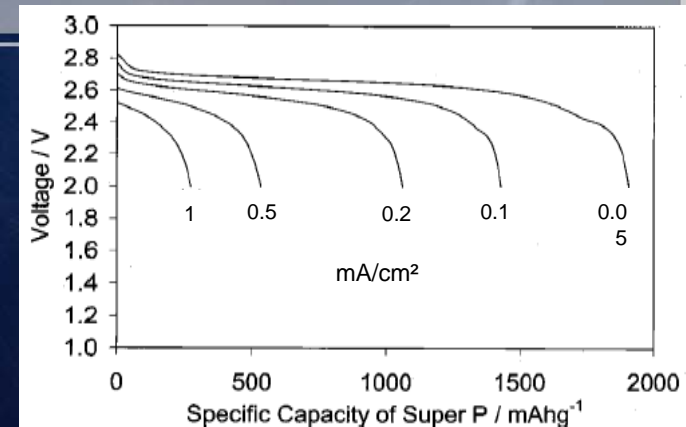
2.5 V avg. with 630 mAh/g carbon, 0.5 mA/cm²

Li-O ₂ & Li-air	Wh/kg	Wh/liter
electrochemical	587	880
pouch cell	473	617

2.3 V avg. with 300 mAh/g carbon, 1.0 mA/cm²

Li-O ₂ & Li-air	Wh/kg	Wh/liter
electrochemical	329	526
pouch cell	279	381

*Projections are for “free” air (neglect O₂ storage)



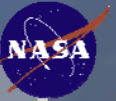
Journal of The Electrochemical Society, 149 (9) A1190-A1195 (2002)

Challenges:

- Recharge capability
- Capacity of carbon to store Li discharge products
- Rate capability

Oxygen storage type	Wh/kg	Wh/liter
steel	375	419
carbon composite	438	427
no storage	473	617





Li-S: ~ TRL 3

Characteristics:

- High specific capacity (1600 mAh/g S theoretical)
- 2-plateau discharge

Projection for 2-plateau discharge
Assume 1000 mAh/g S

Li-S	Wh/kg	Wh/liter
electrochemical	610	864
pouch cell	474	595

Demonstrated in 4 Ah pouch cells (JSC):

- BOL: 393 Wh/kg
- EOL: 256 Wh/kg
- 75 cycles to 80% of initial capacity

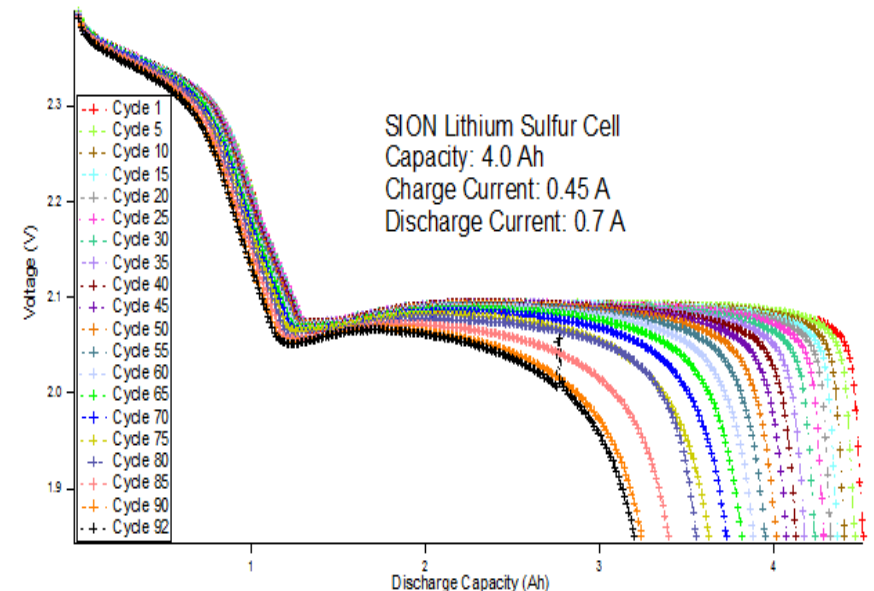
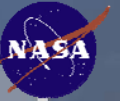


Figure 17: SION Lithium Sulfur Cell ID# 20F Rate Capability Protocol #2 Data

Challenges:

- Safety (rechargeability, lithium dendrite formation)
- Cycle life

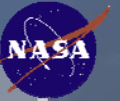




Summary

- Power is needed for all Exploration vehicles & for the mission applications.
- Safe, high-energy/ultra-high energy batteries are required for long-term missions as in Near-Earth Asteroid (NEA) & Mars programs.
- Component-level research will provide higher energy density as well as safer lithium-ion cells for human-rated space applications. The challenge is with scale-up of materials & cell size, & proof of safety in larger cell designs.
- Low temperature and wide temperature range performance are still major challenges.
- Collaborations with other government agencies & industry provide good leverage.
- NRA, grants, SBIR, & STTR allow EP to take significantly good research into production even though space applications require only low-volume production.

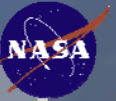




Battery Areas of Work

- International Space Station (ISS)
- Extravehicular Activity (EVA)
- Advanced Cell / Battery Studies
 - Commercial off-the-shelf (COTS) Program
 - Space Power Systems (Batteries)
 - Industry Collaborations
 - Advanced Exploration Systems- Batteries
- Other Projects



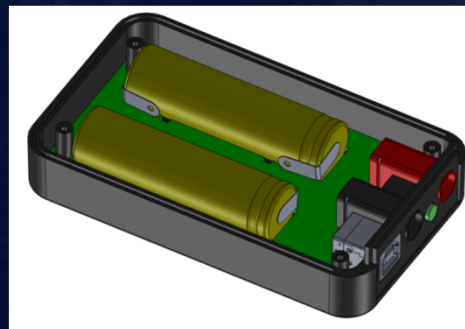


International Space Station (ISS)

(POC: J. Jeevarajan)

Several COTS and small custom-designed li-ion batteries used for payload experiments,

- small satellites (30 to 45 launched per flight);
- Cameras (Canon, Nikon, iPad, iPod, currently working on Ghost and Red)
- Completed manufacturing a semi-COTS 3.7 V, 4.9 Ah li-ion battery for use in portable equipment and experiments- can be used by external series and/or parallel connections for custom designs (LG 2.8 Ah cells ; rated 4.9 Ah is due to restricted voltage range of 4.2 to 3.0 V) semi COTS battery has safety and charger protocol programmed into internal battery circuitry



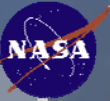
3.7 V 4900mAh
Lithium-Ion
Battery
Part Number: 100490
Serial Number: PROTO1
Output: 4.2 - 3.0 Vdc 9 A max
Charge Input:
Main - 4.2 Vdc 2.8 A max
USB - 5 Vdc 500 mA max
Series Connection: 8 units max



100490-PROTO1

LED	Blink	Status
Green	On	Charged > 95%
Red	On	Charged 10% - 95%
Red	Fast	Charged < 10%
Green	Slow	Charging > 95%
Red	Slow	Charging < 95%
Green	Fast	Fault





EVA Batteries- Current

POC: Eric Darcy, Gilbert Varela

PGT - Pistol Grip Tool

- The Pistol Grip Tool has been used on several EVA missions especially the HST missions.
- The PGT battery has 30 Panasonic NiMH A size cells in a series configuration; 42 V, 2 Ah (200 mA base current draw, 8 A 100 msec peaks –total 2 hr run time)
- The battery is charged as two 15 cell strings using the EHIP charger and cable adapter.
- The cable adapter connects two stations of the EHIP charger.



EHIP: EVA Helmet Interchangeable Portable Battery (helmet light battery)

15 to 22 V and 9 Ah

Load is 0.2 A for 8 hours max

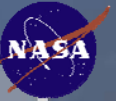
Uses 4/3A Sanyo NiMH cells



REBA – Rechargeable Battery Assembly

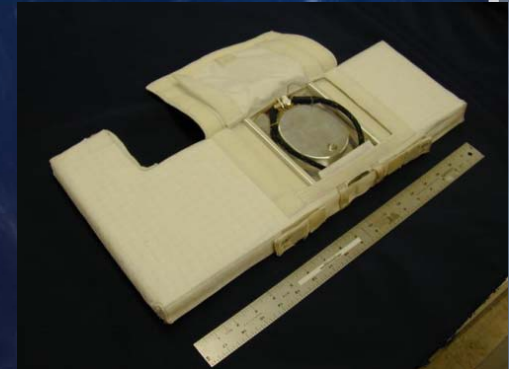
- Battery made up of Sanyo 4/3A NiMH cells in a 5P10S configuration; 12.5 V, 18 Ah (2.33 A for 7 hours)
- First used to power the glove heaters and helmet-mounted video camera (ERCA).

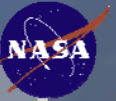




LREBA and LPGT Battery Overview (EVA Battery Upgrades) POC: Sam Russell, Eric Darcy

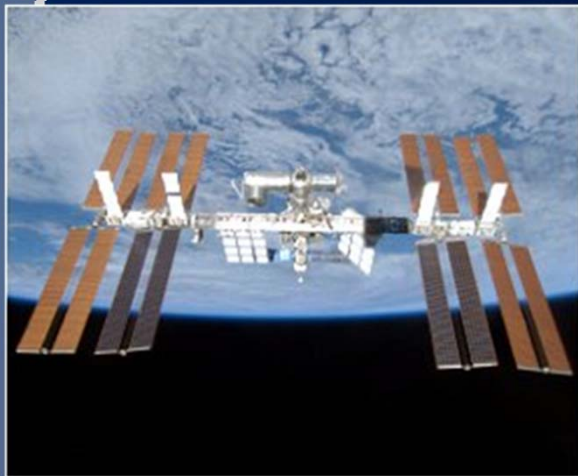
- **Lithium Ion Rechargeable EVA Battery Assembly (LREBA)**
 - 9P-5S battery using commercial 18650 electrochemical cells
 - Designed to exceed the combined EHIP and REBA loads
 - Dedicated charge and discharge interface (21.6Ahr)
 - Discharge configuration provides regulated 13.5V output
 - Service connector provides EBOT required telemetry at 20.5V
 - Preserve existing interfaces while improving handling robustness
- **Lithium Ion Pistol Grip Tool (LPGT) Battery Assembly**
 - Multi-interface battery using commercial 18650 electrochemical cells
 - Charge configuration as 2P-5S battery (20.5V, 4.8Ahr)
 - Discharge configuration as 1P-10S battery (41V, 2.4Ahr)
 - Designed to meet or exceed tool runtime
 - Preserve existing tool interface while improving crew interface
- **Common to both designs**
 - 18650 Commercial Cell
 - Stored and serviced IVA in EBOT
 - No change in discharge and physical interfaces
 - Hazard control similar to Long Life EMU Li-ion Battery
 - Current limiting device(s) for external short hazard
 - Circuit interrupt device(s) for over-charge hazard
 - Low voltage cut-off for regulated LREBA output
 - Design for Minimum Risk cell selection and screening



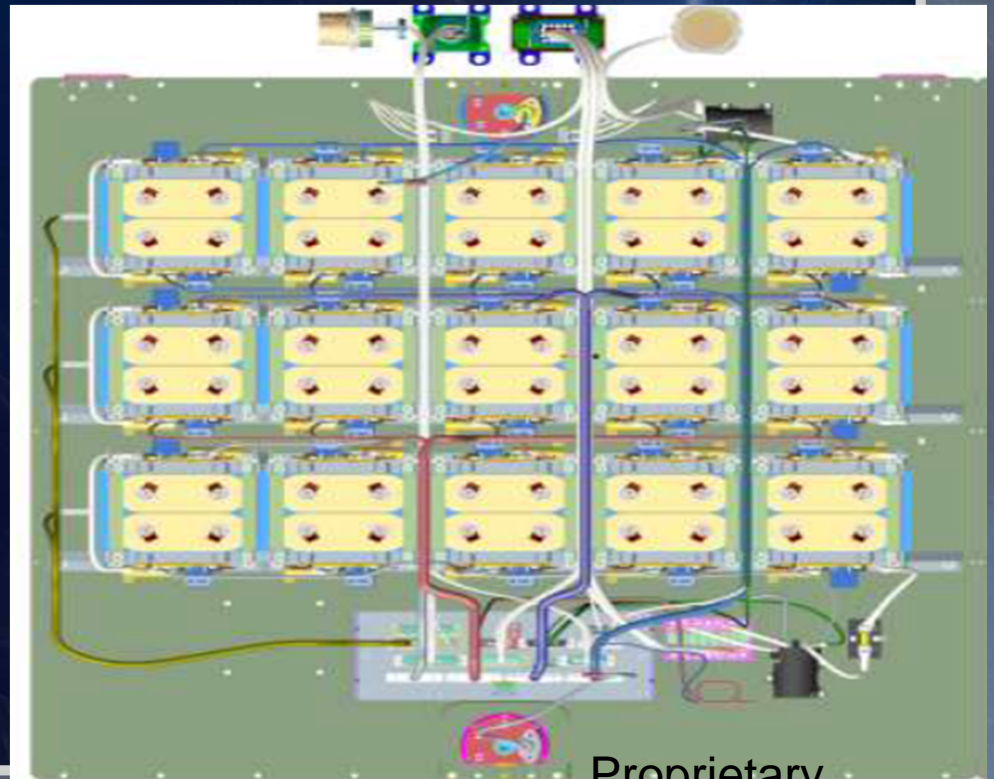


ISS Battery Upgrade (Subsystem Manager: Penni Dalton Safety Panel POC: J. Jeevarajan)

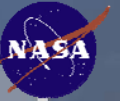
- A new Li-ion battery will replace the existing NiH₂ battery chemistry. NASA-Glenn leads the Program (POC: Penni Dalton). NASA-JSC provides support with safety testing as well as safety guidance.



134 Ah GS Yuasa Li-ion Cells
30S configuration



Proprietary 



Advanced Cell / Battery Assessments

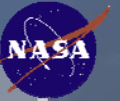
POC: J. Jeevarajan

- **Li-Ion Polymer/Pouch Cells (Advd. Battery technology)**
 - **Cycling and storage tests under vacuum and reduced pressure conditions completed and presented at conferences**
 - SKC- 15 Ah
 - Tenergy
 - Wanma
 - Altairnano
 - Kokam
 - GMB

Outcome: Flight batteries using pouch/polymer cells are subjected to reduced pressure (8 to 10 psi) leak checks rather than vacuum or deep space vacuum conditions for leak checks.

- **Li-Ion High Energy Density**
 - LG 18650 3.0 Ah (safety and performance)
 - LG 18650 pouch/polymer (safety and performance)
- **Other Tests (Advd. Battery technology)**
 - Low temperature effects on safety of commercial li-ion cells
 - Safety Characteristics of Li-ion cells at different states of charge
 - Cell to cell thermal runaway propagation study – 18650 cell design and Boston Power prismatic cell design – 9S, 4S, 4P designs studied with air space, radiant barriers and intumescent material





Space Power Systems Batteries

POC: J. Jeevarajan

- JSC's responsibility was in safety testing
- Four versions of the 7 Ah cells were manufactured of which two sets have completed testing and the third set is under test now.
- Initial set of tests indicated that the flame-retardant electrolyte additive synthesized by JPL provided safety under overcharge and external short conditions; unable to replicate the results in 7 Ah cells.
- Key Performance Parameters for Project provided on next page.



Key Performance Parameters for Battery Technology Development

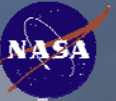
Customer Need	Performance Parameter	State-of-the-Art	Current Value	Threshold Value	Goal
Safe, reliable operation	No fire or flame	Instrumentation/controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA	Preliminary results indicate a moderate reduction in the performance with flame retardants and non-flammable electrolytes	Benign cell venting without fire or flame and reduce the likelihood and severity of a fire in the event of a thermal runaway	Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and external short circuit with no fire or flame
Specific energy <u>Lander:</u> 150 – 210 Wh/kg 10 cycles <u>Rover:</u> 150 – 200 Wh/kg <u>EVA:</u> 200 – 300 Wh/kg 100 cycles	Battery-level specific energy*	90 Wh/kg at C/10 & 30°C 83 Wh/kg at C/10 & 0°C (MER rovers)	130 Wh/kg at C/10 & 30°C 120 Wh/kg at C/10 & 0°C	135 Wh/kg at C/10 & 0°C “High-Energy”** 150 Wh/kg at C/10 & 0°C “Ultra-High Energy”**	150 Wh/kg at C/10 & 0°C “High-Energy” 220 Wh/kg at C/10 & 0°C “Ultra-High Energy”
	Cell-level specific energy	130 Wh/kg at C/10 & 30°C 118 Wh/kg at C/10 & 0°C	150 Wh/kg at C/10 & 0°C	165 Wh/kg at C/10 & 0°C “High-Energy” 180 Wh/kg at C/10 & 0°C “Ultra-High Energy”	180 Wh/kg at C/10 & 0°C “High-Energy” 260 Wh/kg at C/10 & 0°C “Ultra-High Energy”
	Cathode-level specific capacity Li(Li,NiMn)O ₂	140 – 150 mAh/g typical	Li(Li _{0.17} Ni _{0.25} Mn _{0.58})O ₂ : 240 mAh/g at C/10 & 25°C Li(Li _{0.2} Ni _{0.13} Mn _{0.54} Co _{0.13})O ₂ : 250 mAh/g at C/10 & 25°C 200 mAh/g at C/10 & 0°C	260 mAh/g at C/10 & 0°C	280 mAh/g at C/10 & 0°C
	Anode-level specific capacity	320 mAh/g (MCMB)	320 mAh/g MCMB 450 mAh/g Si composite	600 mAh/g at C/10 & 0°C with Si composite	1000 mAh/g at C/10 0°C with Si composite
Energy density Lander: 311 Wh/l Rover: TBD EVA: 240 – 400 Wh/l	Battery-level energy density	250 Wh/l	n/a	270 Wh/l “High-Energy” 360 Wh/l “Ultra-High”	320 Wh/l “High-Energy” 420 Wh/l “Ultra-High”
	Cell-level energy density	320 Wh/l	n/a	385 Wh/l “High-Energy” 460 Wh/l “Ultra-High”	390 Wh/l “High-Energy” 530 Wh/l “Ultra-High”
Operating environment 0°C to 30°C, Vacuum	Operating temperature	-20°C to +40°C	-50°C to +40°C	0°C to 30°C	0°C to 30°C

Assumes prismatic cell packaging for threshold values. Goal values include lightweight battery packaging.

* Battery values are assumed at 100% DOD, discharged at C/10 to 3.0 volts/cell, and at 0°C operating conditions

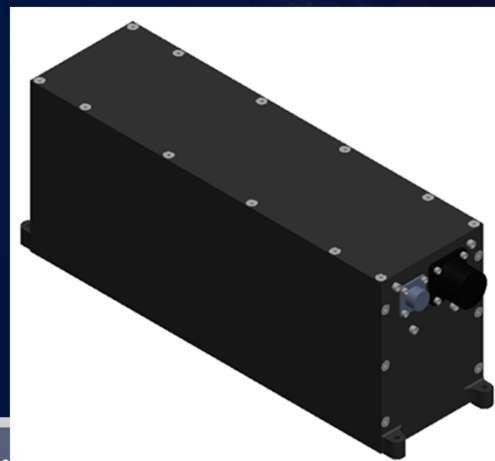
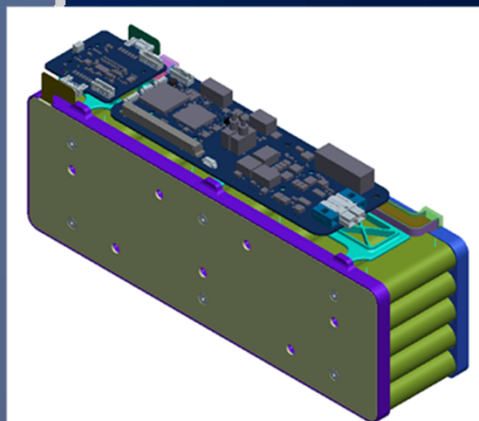
** “High-Energy” = Exploration Technology Development Program cathode with MCMB graphite anode

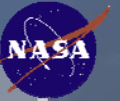
“Ultra-High Energy” = Exploration Technology Development Program cathode with Silicon composite anode



Advanced Exploration Systems Modular Power Systems – Batteries POC: J. Jeevarajan

- The AES Modular Power System (AMPS) is focused on building batteries to provide power to the future Advanced EVA (Extravehicular Activity) Astronaut Suit.
- Two battery designs were– one at JSC and one at Glenn Research Center (GRC)
 - Testing complete at JSC; 402 minutes under current EMU power profile; 3 hours 47 minutes under new Advd Suit mission profile; tested for safety and under deep vacuum conditions and no change in performance under deep vacuum conditions.
 - Next year's plan is to use other cell designs including those with inherent safety and look at using a distributed battery system rather than one large battery.





Lithium Battery Operations Terminal

POC: Martin Martinez

Background:

The EVA Battery Operations Terminal (EBOT) is contractor-provided GFE that is replacing the Battery Charger Assembly / Battery Stowage Assembly (BCA/BSA) in the ISS Joint Airlock avionics rack. EBOT is responsible for charging and discharging the US EVA batteries (LLB, LREBA (in development), and LPGT (in development)) to maintain them for EVA readiness.

Team Organization

XA, OSS (OneEVA), EP5

Major Upcoming Events

Milestone	Plan	ECD
Phase 1 FMEA-CIL / RAESR	4/22/2014	4/30/2014
Delta Phase 1 SRP	N/A	9/17/2014
Charger PDR / Ancillary SDR	8/18/2014	10/15/2014

EBOT



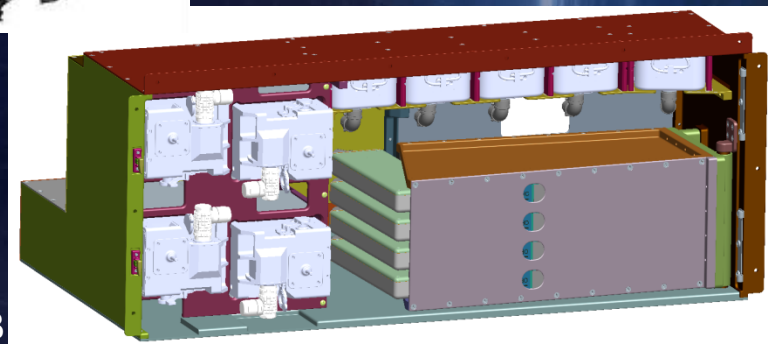
Chargers

Cables



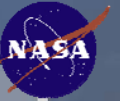
LPGT

LLB



Battery Stowage Compartment





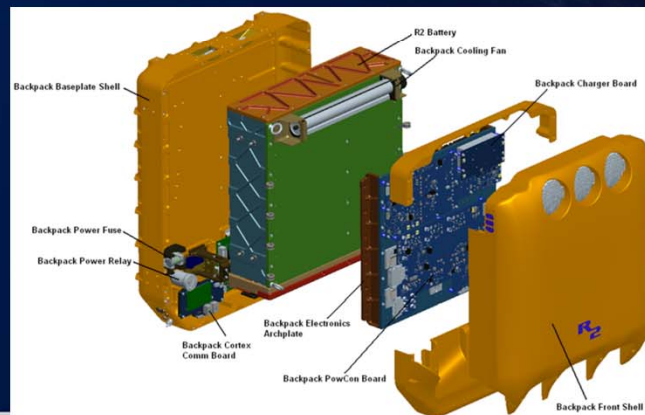
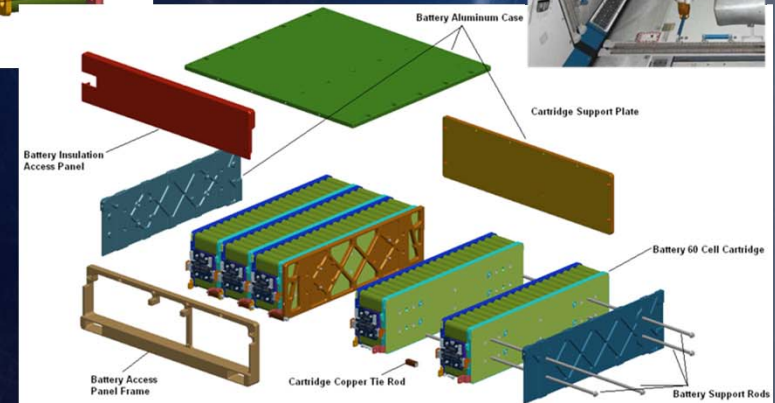
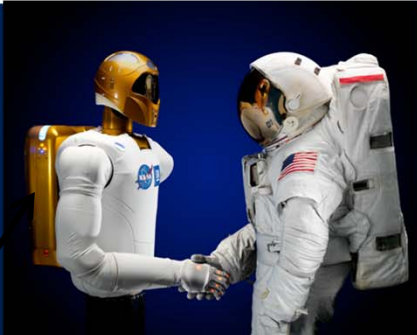
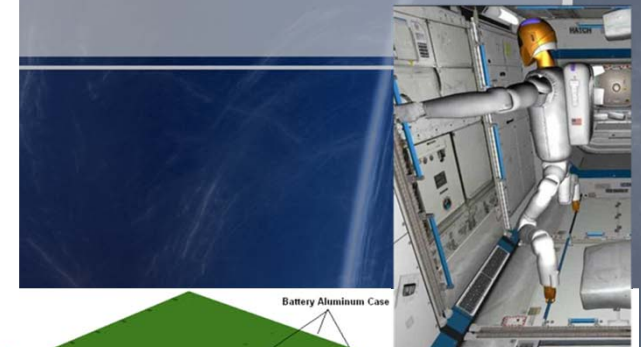
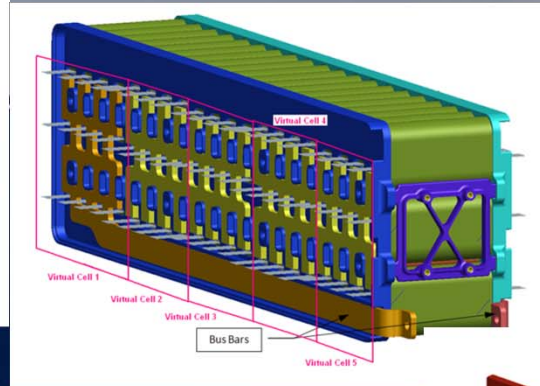
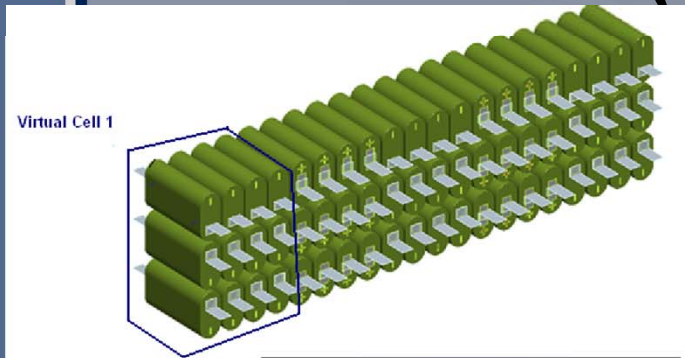
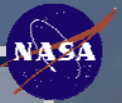
Other Collaborative Work Fine Water Mist Extinguisher

- JSC Hardware team completed work on a fine water fire extinguisher and tested it on camcorder batteries.
- New extinguisher to be used on ISS. Extinguisher in flight test phase.



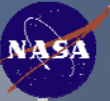
Other Collaborative Work

R2 (Robonaut) Battery



Robonaut battery characteristics
 91 V / 63 Ah nominal (105 to 68.75 V)
 5.3 Ah Boston Power lithium-ion cells
 12 P 25S
 12P (virtual cell or module) config.
 gives the required capacity
 12P5S forms a single cartridge
 and 5 of those cartridges are further
 tied in series to provide the required
 voltage.





Orion Crew Module (CM) Battery Overview

(POC: Eric Darcy, Ramon LeBron and Chuck Havnes)

Component Name:
Crew Module Battery

Description:

The CMB consists of the lithium ion cells, a battery switch, battery fuse, negative leg current sensor, and charge balance control system. The CMB will be one of 4 batteries placed directly on a bus with a solar array current source. The solar array current source is voltage clamped/limited so that battery total voltage limits are not exceeded.

Materials:

Supplier: Yardney Technical Products

Heritage: MSP01, XSS-11, Phoenix lander, NEXTSat

Voltage: 120V

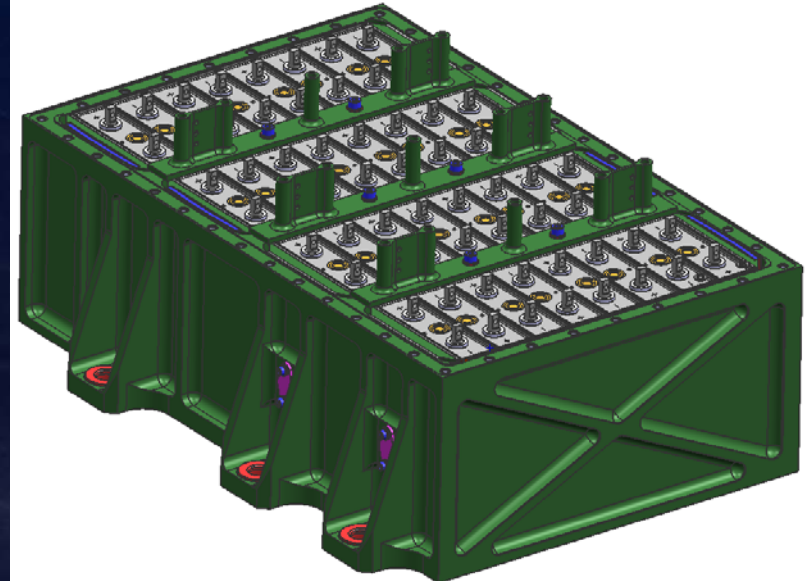
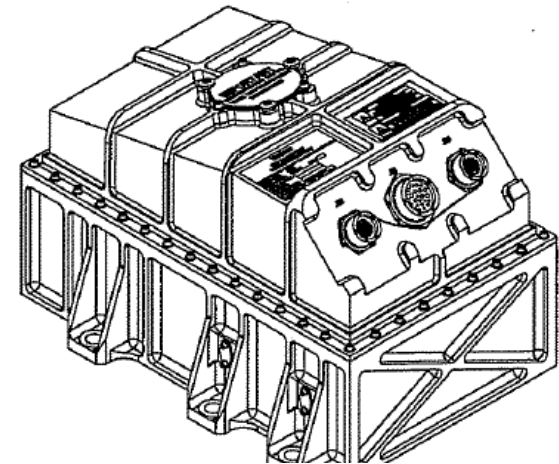
Capacity: 38Ah

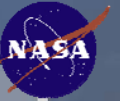
Mass: ~102 lbs,

Envelope Volume: Height 13.4" x Length 17.7" x Width 13.6"

Operating Temp Range: 50 to 104 °F

Storage Temp Range: 12 to 86 °F





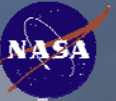
Other Work

- Commercial Crew and Cargo
(POCs from various NASA Centers)

- Boeing
- SpaceX
- Sierra Nevada Corp
- United Launch Alliance (Boeing and SNC for Launch Vehicle)

All vehicles have high and low voltage batteries; competing for next phase; hence blackout period.



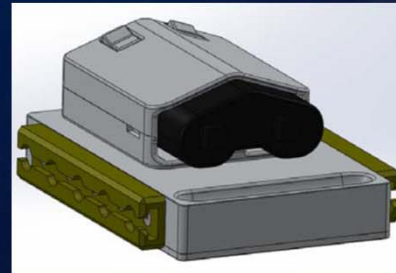
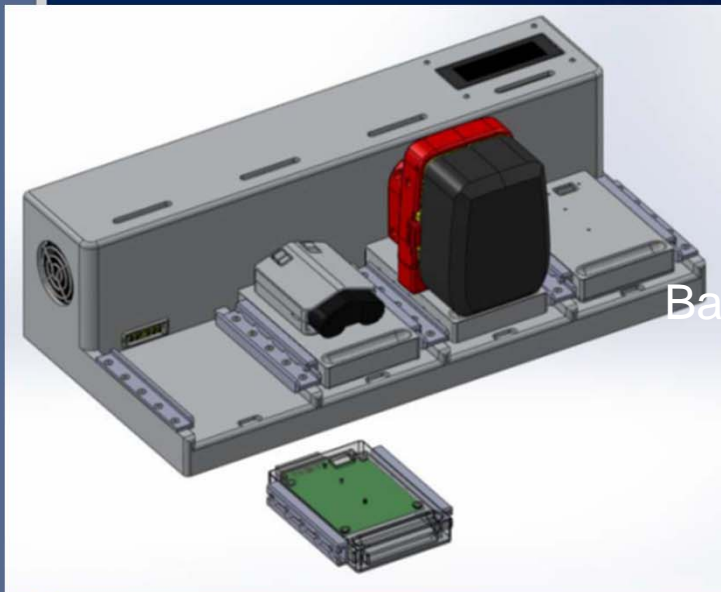


Other Work SBIR Phase II

Aurora Flight Sciences

Universal Battery Charger (UBC) in Phase IIE/Phase III stage.

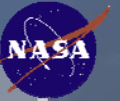
PDR for UBC completed in April, 2013. Plans to complete flight charger by Sept. 2015.



Batteries that can be charged using relevant adapters

Part Number	Manufacturer	System Type	Chemistry	Voltage (VDC)	Capacity (mAh)
BP-930	Canon	Camcorder	Li-Ion	7.2	4400
BP-955	Canon	Camcorder	Li-Ion	7.2	5200
CGA-D54	Panasonic	MiniDV digital camcorder	Li-Ion	7.2	5400
EN-EL4a	Nikon	Digital Camera	Li-Ion	11.1	2500
TE2-1-0800-000	Aurora Flight Sciences	SPHERES- ISS Testbed	Li-Ion	11.1	1950
VW-VBG6PPK	Panasonic	AVCCAM Camcorder	Li-Ion	7.2	5400
DC9180	DeWalt	Power Tool	Li-Ion	18	2200

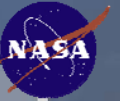




Update to Battery Safety Requirements Document

- JSC 20793 Crewed Space Vehicle Battery Safety Requirements
 - Document was Rev B
 - Updates completed in December 2013.
 - Accepted by Commercial Crew and Cargo and included in current Rev of their Requirements document (CCTS 1130 and 1140)
 - ISS process almost complete; no major concerns expressed by stake holders with changes made

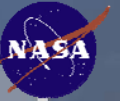




Update to Battery Safety Requirements Document

- Crewed Space Vehicle Battery Safety Requirements, JSC 20793
 - Began as a Handbook in '85; Used widely throughout Agency in handbook form
 - Converted to requirements document (standard) in 2005
 - Current version is Rev B. (2006)
 - Only battery safety standard within Agency
- The need for an update to JSC 20793 was required due to
 - NASA battery teams have learned a lot since the document was last updated especially on chemistries such as li-ion based on internal and external test data and experience
 - After NASA support to Dreamliner, internal technical team confirmed the need to revise the standard bringing it up to date and incorporating lessons learned from 787
 - The extensive use of high voltage and high capacity Li-ion batteries
 - Use of Thermal batteries for commercial crew and cargo and Orion launch systems
 - Use of Supercapacitors in the place of batteries, etc.
- The format was revised to follow NASA standards template
 - Requirement based format with italicized text included explanatory, best practice, and rationale information.
 - Added glossary and numerous appendices (qual testing, requirements matrix, approval process, etc.)





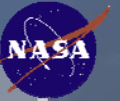
Significant Addition

5.1.5.1 Requirements – Thermal Runaway Propagation

- a. For battery designs greater than a 80-Wh energy employing high specific energy cells (greater than 80 watt-hours/kg, for example, lithium-ion chemistries) with catastrophic failure modes, the battery shall be evaluated to ascertain the severity of a worst-case single-cell thermal runaway event and the propensity of the design to demonstrate cell-to-cell propagation in the intended application and environment.

- b. The evaluation shall include all necessary analysis and test to quantify the severity (consequence) of the event in the intended application and environment as well as to identify design modifications to the battery or the system that could appreciably reduce that severity.





Acknowledgments

- Coworkers in Power Systems Branch at JSC & other NASA Centers
- Collaborators in industry & academia

